

PeV NEUTRINOS FROM ULTRA-HIGH-ENERGY COSMIC RAYS

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We investigate the possibility that the recently detected TeV-PeV neutrino events by IceCube can originate from extragalactic ultra-high-energy cosmic ray interactions with the cosmic microwave background or the UV/optical/IR background. This is done by simulating the propagation of the cosmic rays from their sources to the observer, including the production and propagation of secondary neutrinos and gamma rays. For this purpose we use the publicly available simulation package CRPropa 2.0. We find that in all the scenarios considered here the simulated neutrino flux level remains at least one order of magnitude below the flux level indicated by the IceCube events, thus showing it is difficult to interpret the IceCube events in terms of a cosmogenic neutrino flux.

1 Introduction

When ultra-high-energy cosmic rays (UHECRs) traverse the universe they interact with extragalactic background light like the cosmic microwave background (CMB) and the UV/optical/IR background (IRB). One possible interaction with the CMB or IRB is photopion production. In this case the process $p + \gamma \rightarrow n + \pi^+$ will produce neutrinos from the decay of the neutron as well as from pion decay. When the UHECRs are nuclei instead of protons these nuclei can be photodisintegrated by photons from the CMB or IRB. In this way single neutrons can be separated from the nuclei, which will again decay and produce neutrinos. The nuclei themselves could also become unstable in this way and emit neutrinos in their decay. Here we investigate whether the recently observed neutrinos by IceCube with energies between 30 TeV and 2 PeV [1] could have originated from such interactions. This proceeding is based on Ref. [2], done in collaboration with Silvia Mollerach and Esteban Roulet.

The IceCube collaboration first detected two PeV neutrino events [3], the highest energy neutrino events observed up till now. After improving their sensitivity and extending their energy coverage down to around 30 TeV, 26 additional events were observed [4]. With one year more of data this increased to a total of 37 events [1]. These observations reject a purely atmospheric origin for all events at the 5.7σ level. The best-fit E^{-2} astrophysical spectrum with a per-flavor normalization (1 : 1 : 1) to these events suggests a flux level of $E_\nu^2 d\Phi_\nu/dE = 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ in the 100 TeV - PeV range.

To simulate the propagation of UHECRs and their secondary neutrinos and gamma rays, we used the publicly available simulation package CRPropa 2.0 [5], as was done in Ref. [2]. CRPropa includes all relevant interactions as well as cosmological and source evolution and redshift scaling of the background light intensity in one dimensional (1D) simulations.

2 Neutrino fluxes from UHECR protons

For UHECR protons interacting with the CMB, the average neutrino energy from neutron decay for a typical neutrino production redshift of $z = 1.2$ is $E_\nu \approx 6 \times 10^{15}$ eV, while the average neutrino energy from the pion decay chain is $E_\nu \approx 10^{18}$ eV [2]. Wide peaks around these energies are expected due to a wide Δ resonance, a wide thermal spectrum of CMB photons as well as due to contributions from a wide range of redshifts.

For UHECR protons interacting with the IRB, the neutrino energy from neutron decay is typically $E_\nu < 10^{14}$ eV, while the average neutrino energy from the pion decay chain is $E_\nu \approx 8 \times 10^{15} / [(1+z)(E_\gamma/\text{eV})]$ eV, with R_{max} the energy of the background photon. The later is expected to give the dominant contribution to the neutrino flux in the PeV range [2].

Here we show the resulting spectra by simulating the propagation of UHECR protons from their sources to the observer with CRPropa 2.0. We use 1D simulations including pair production, pion production and all relevant decay channels. Furthermore, for all simulations, cosmological and source evolution as well as redshift scaling of the background light intensity are included. The IRB considered, including its redshift evolution, is the 'best-fit model' of Ref. [6]. For this case a pure proton spectrum with a spectral index of $\alpha = 2.4$, a minimum energy of 2×10^{16} eV and a sharp cutoff at $E_{\text{max}} = 200$ EeV has been injected at the sources. A continuous source density following a redshift evolution (for the density times CR emissivity) according to the gamma-ray burst evolution has been adopted. This source evolution corresponds to the SFR6 model derived in Ref. [7] and is here referred to as GRB2.

The results are shown in fig. 1. The simulated CR spectrum has been normalized at 10 EeV to the spectrum measured by the Pierre Auger Collaboration [8] as presented during the ICRC 2013 [9]. This spectrum has a 14% systematic uncertainty on the energy scale, which is not shown in the figures. The overall shape of the simulated spectrum is in reasonable agreement with the measured spectrum. The all-flavor neutrino spectrum has been normalized accordingly. The bounds on the all-flavor neutrino flux obtained by IceCube [10], Pierre Auger [9] and Anita [11] are displayed as well. It is clear that the simulated neutrino flux remains far removed from the neutrino bounds as well as from the IceCube flux level.

Additionally, in fig. 1(b), the cascade photons originating from UHECR interactions with the CMB and IRB are shown. They nearly reach the diffuse gamma-ray flux level observed by Fermi [12].

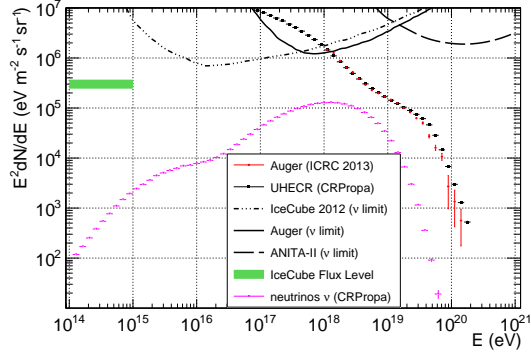
The neutrino flux is expected to increase when, instead of the GRB2 source evolution, a stronger source evolution as for instance the AGN evolution model of Ref. [13] (here referred to as FRII) is implemented. This is confirmed by the simulation results in fig. 2. In this case, instead of $\alpha = 2.4$, a spectral index of $\alpha = 2.2$ at the sources was set, as this, for this scenario, produces a closer resemblance to the measured UHECR spectrum. All other parameters have remained the same.

However, as visible from fig. 2, not only the neutrino flux but the photon flux increases with a stronger source evolution as well. Whereas the simulated neutrino flux is still far removed from the IceCube flux level, the gamma-ray flux is on the verge of conflicting with the diffuse gamma-ray flux level observed by Fermi.

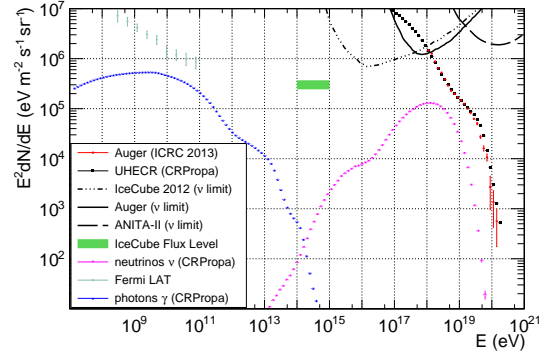
Compared with Ref. [2] the Pierre Auger UHECR spectrum, Pierre Auger neutrino limit, IceCube neutrino flux level and IceCube neutrino limit have been updated. Furthermore, for these simulations an updated version of CRPropa 2.0 (CRPropa v2.0.4) was used, which includes an improved energy interpolation for the pion production.

3 Neutrino fluxes from iron nuclei

When considering nuclei heavier than protons, photodisintegration can play an important role. If a nuclei photodisintegrates completely, about half of the emitted nucleons will be neutrons, which then decay to produce neutrinos. The energy of these neutrinos, for interactions with the



(a) Proton sources, $\alpha = 2.4$, $E_{\text{max}} = 200$ EeV, GRB2



(b) Including cascade photons

Figure 1 – Pure proton injection at the sources, with a spectral index at injection of $\alpha = 2.4$ and a maximum energy of $E_{\text{max}} = 200$ EeV. The GRB2 source evolution model has been implemented. (a) In the left panel in red points the measured Pierre Auger UHECR spectrum is shown, while in black points the simulated UHECR spectrum is given. The lines show the bounds on the all-flavor neutrino flux by IceCube (dashed dotted), Pierre Auger (straight) and Anita (dashed). The green area indicates the flux level of the IceCube events. The magenta points show the simulated neutrino flux. (b) The same spectra, bounds and flux level are given in the right panel as well. Furthermore, the diffuse gamma-ray flux observed by Fermi and the simulated gamma-ray flux from UHECR interactions are shown.

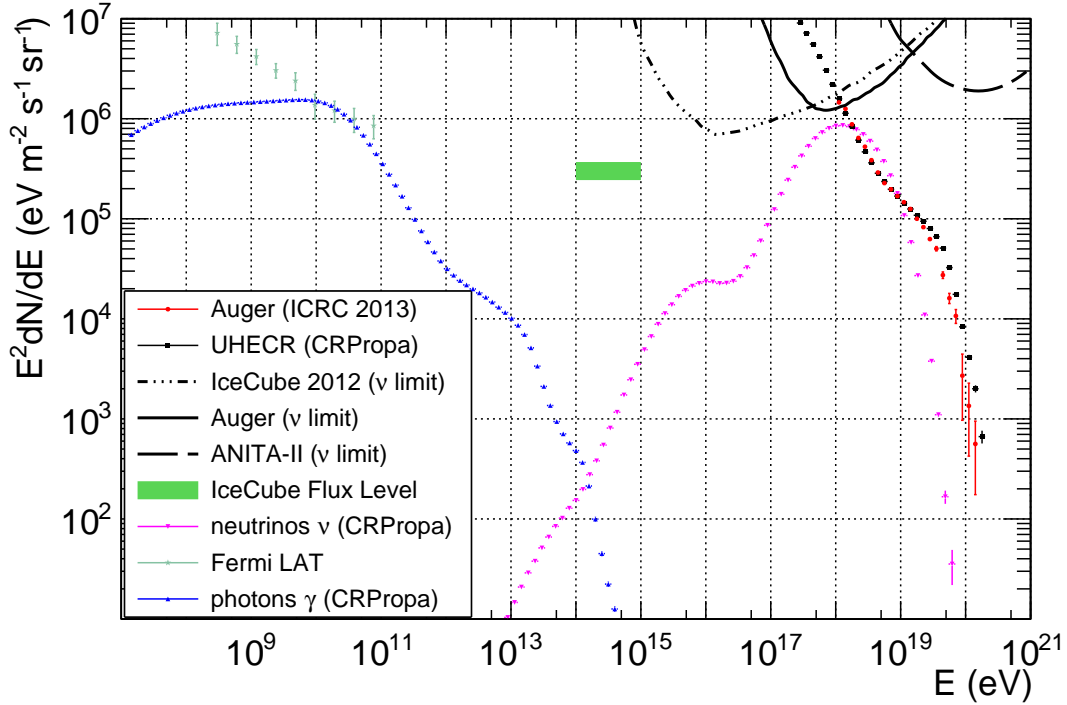


Figure 2 – Pure proton injection at the sources, with a spectral index at injection of $\alpha = 2.2$ and a maximum energy of $E_{\text{max}} = 200$ EeV. The FRII source evolution model has been implemented. The same simulated spectra, measurements, limits and flux level are shown as in fig. 1(b).

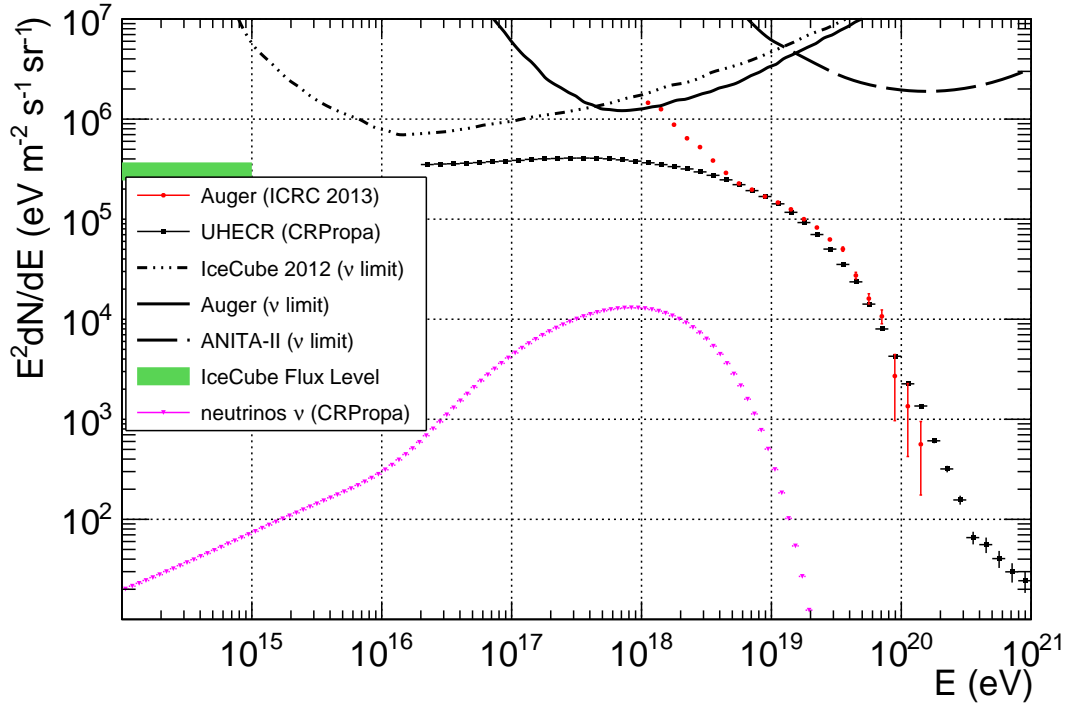


Figure 3 – Pure iron injection at the sources, with a spectral index at injection of $\alpha = 2.0$ and a maximum energy of iron of $E_{\text{max}} = 5200$ EeV. The GRB2 source evolution model has been implemented. The same spectra, limits and flux level are shown as in fig. 1(a). Compared with fig. 1(a) the neutrino flux has decreased due to the heavier composition.

CMB background, will typically be around $E_\nu \approx \text{few} \times 10^{14}$ eV [2]. Photopion production of nuclei on the CMB and IRB is possible as well, however its threshold energy is a factor A times higher than in the pure proton case, where A is the mass number of the nucleus. This does give rise to the production of PeV neutrinos by photopion production of IRB photons, but at a level which is expected to be lower than that achievable in proton scenarios [2].

This statement is confirmed by fig. 3, which was obtained by simulating pure iron injection at the sources, with a spectral index of $\alpha = 2.0$ and a sharp cutoff at $E_{\text{max}} = 5200$ EeV. In this case the GRB2 source evolution model was implemented. All other simulation parameters are the same as in the proton injection cases. The shape of the simulated spectrum is in reasonable agreement with the measured spectrum above the ankle.

4 Neutrino flux for low E_{max} and mixed composition

Note that a lower maximum energy can drastically reduce the neutrino peak at around 10^{18} eV, but is not expected to significantly reduce the PeV neutrino flux for the pure iron injection case. In fig. 4 a mixed-composition scenario is shown with proton and iron injected at the sources, a spectral index at injection of $\alpha = 2.0$, a maximum rigidity of $R_{\text{max}} = E_{\text{max}}/Z = 5$ EV (with Z the charge of the injected nucleus) and the GRB2 source evolution model. The ratio between injected proton and iron nuclei is $n_p/n_{Fe} = 250$ at a given energy per nucleon E/A . It is clearly visible that the EeV neutrino peak has been reduced drastically due to the low maximum energy, while the neutrino flux at the PeV level has instead increased with respect to the one in fig. 3 due to the additional proton primaries. In this case the shape of the simulated spectrum is in reasonable agreement with the full measured spectrum, while in the pure iron case it only resembled the spectrum above the ankle.

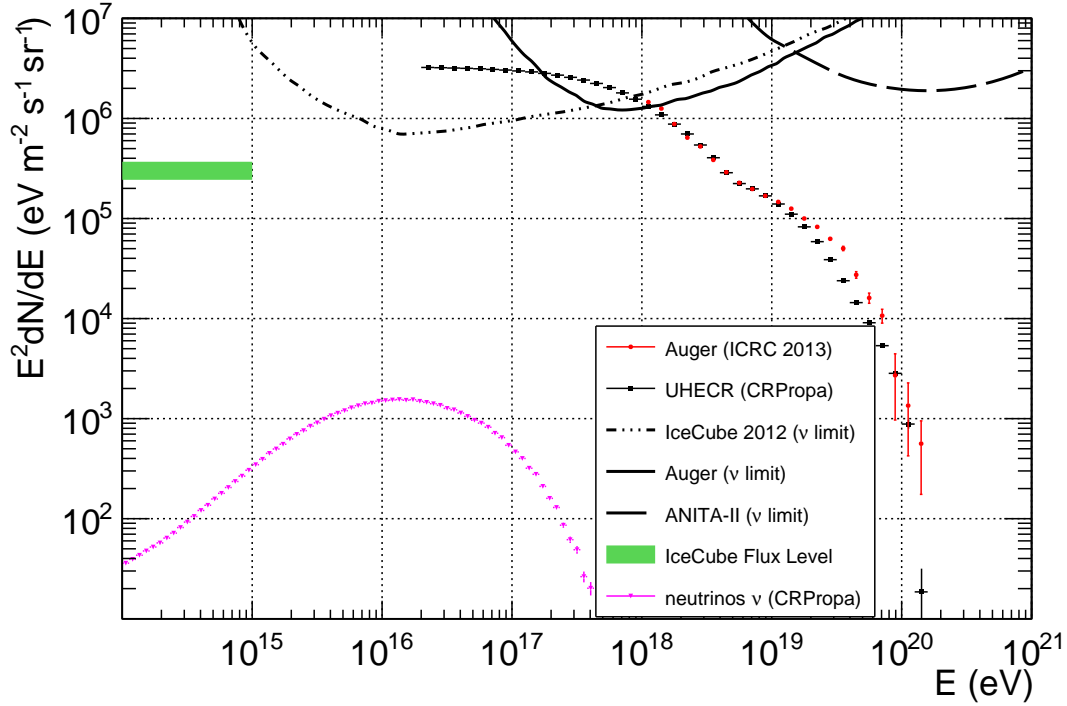


Figure 4 – Proton and iron injection at the sources, with a ratio of $n_p/n_{Fe} = 250$ at a given E/A . The spectral index at injection is $\alpha = 2.0$ and the UHECRs are injected up to a maximum rigidity of $R_{\max} = 5$ EV. The GRB2 source evolution model has been implemented. The same spectra, limits and flux level are shown as in the previous cases. The neutrino flux at EeV energies is reduced drastically due to the relatively low R_{\max} , while at PeV energies it has increased compared to the pure iron case of fig. 3 due to the additional proton component.

5 Conclusions

For all the scenarios presented here the simulated neutrino flux remains at least one order of magnitude below the flux level indicated by the events measured by IceCube. When implementing stronger source evolution models the expected neutrino flux can be enhanced. However, when taking into account the secondary gamma-ray flux, it is clear that the source evolution can not be enhanced too much in order not to exceed the diffuse gamma-ray flux observed by Fermi. Going to a heavier composition than pure proton injection only decreases the neutrino flux at the PeV level. So for all the scenarios considered here it is difficult to interpret the IceCube events in terms of a cosmogenic neutrino flux, unless the IceCube events are a strong upward fluctuation of the expected neutrino rates.

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